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A fast numerical modelling approach based on boundary field method for calculating AC losses in superconducting motors

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Abstract— To improve the computational efficiency of the numerical methods for calculating AC loss in HTS motor, a new method called ‘Boundary field method’ is proposed in this paper. This method combines the strength of ANSYS and COMSOL, which can reduce the complexity of modeling and computation time. In this paper, three finite element method (FEM) based models, as case studies, were developed for a 100-kW superconducting induction motor. Model A models entire motor in COMSOL using A-H formulation, considering non-linear E - J relationship of HTS tapes, which can calculate AC loss of motor directly; Combining another two models: Model B (the same entire superconducting motor in ANSYS) and Model C (only superconducting stator windings in COMSOL) can achieve new method for calculating AC loss. The AC loss calculation error between two methods for two-layer windings in one slot is 2.5% and 7%, respectively. These results conclude the effectiveness and accuracy of ‘Boundary field method’. More importantly, the computation time reduces dramatically from 48 hours in Model A to only 2 hours for proposed approach. This accurate and computationally efficient new numerical modelling approach could be used to calculate AC loss in various types of superconducting applications in future.

Index Terms—AC loss, Boundary field method, HTS motor, magnetic field distribution

I. INTRODUCTION

HIGH temperature superconducting (HTS) motors exhibit many advantages compared with the conventional copper counterparts, such as compact size and high power density [1]. Both partially and fully HTS motors were developed in literature aiming for maximizing power density in different applications[2-5]. However, high AC loss in HTS armature winding imposes challenge on cryogenic cooling system, and it is a key issue requiring solution to enable practical application of HTS machine especially for electric aircraft [6].

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To date, researchers have proposed different finite element method (FEM) based models to evaluate the AC loss for HTS. In [7], hybrid models using mixed H and A formulation frameworks were developed to model superconducting rotating machine. However, usually models based on H-formulation suffer high computation cost and slow speed[8, 9]. Recently, T-A formulation as an alternative to the H-A formulation was proposed and used for simulating HTS machines, which greatly reduces the computation time [10-13]. These modelling formulations were done using the commercially available COMSOL Multiphysics, which is very convenient to define non-linear properties of HTS materials in. However, if using this type of models, often entire motor model needs to be built to ensure high accuracy, as a result the computation time would be very long, i.e., about several days compared with tape or winding models which can be solved just in a couple of hours. In addition, dividing the model into superconducting, non-superconducting regions, stationary and non-stationary regions significantly increase the complexity of modeling procedure.

Meanwhile, another FEM based software package, ANSYS, has an incomparable motor analysis module, Maxwell, which can easily model the motor and calculate the model parameters quickly. However, compared with COMSOL, calculating AC loss of HTS material in ANSYS is more complex because users need to have programming ability. For example, in [14, 15], the magnetization of a HTS bulk was modeled by using the ANSYS A-V-A formulation-based iterative algorithm method. In [16], a 3D HTS generator model was established in ANSYS, and the maxwell’s equation and power-law equation are formulated in diversity of formulation namely A-V method. In [17], AC loss of HTS winding was calculated using the ANSYS combined with the resistivity-adaption algorithm.

To improve the computational efficiency of numerical method for calculating AC loss in HTS motor. In this paper, we proposed an efficient and fast AC loss calculation method called ‘boundary field method’ by taking advantage of both ANSYS in modelling of the machines, and COMSOL in defining HTS materials properties. The idea behind ‘boundary field method’ is to transfer AC loss calculation of an entire motor model into that of in winding model. Interpolation function in COMSOL play a key role in achieving this idea by adding real and accurate motor magnetic environment in winding model.

For explanation and verification of this new method specifically, based on a 100 kW HTS motor, three FEM models, as

case studies, were developed. This paper is structured as follows. Section II, we overview the specifications of the objective motor, meanwhile the characteristics of three models and the relationship between them are introduced as well. Section III presents the simulation results of models. Through comparison and discussion, it is proved that the new method of calculating AC loss is reasonable. Finally, we summarize the article in the section IV.

II. NUMERICAL MODELING METHODOLOGY

A. 100 kW HTS induction Motor

A 100 kW, 6000 rpm HTS induction motor is chosen as an analysis object. The topology of this motor is adopted from the motor proposed in [18], which is a partial superconducting induction motor with (RE)BCO armature winding. Fig.1 presents the winding arrangement. The main parameters of the motor are listed in Table I. In addition, the (RE)BCO conductors used in this motor are manufactured by ASMC and the main parameters of HTS conductors are given in Table II.

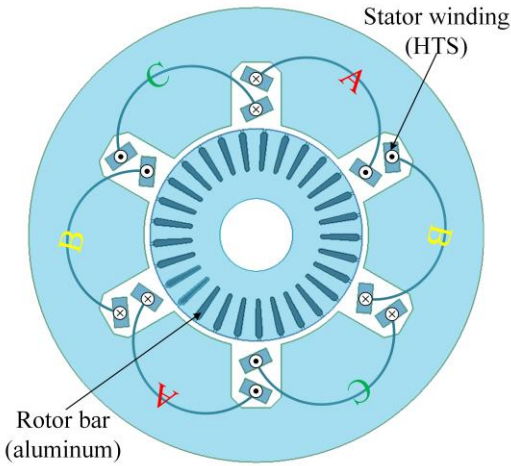


Fig. 1. Three-phase stator winding arrangement diagram (A, B, C show the three phases)

TABLE I
MAIN PARAMETERS OF THE MOTOR DESIGN

Parameters	Value (mm)
Stator outer diameter	345
Stator inner diameter	170
Rotor outer diameter	161
Air-gap length	4.5
Core length	200
Stator slot height	45
Stator slot width	30
Number of rotor slots	33

TABLE II
SPECIFICATIONS OF THE (RE)BCO COATED CONDUCTOR

Parameters	Value
Tape width	4.8 mm
Strip thickness	0.18 mm
Superconducting layer thickness	1 μ m
Minimum bend radius	50 mm
Maximum rated tensile stress	150 MPa
Maximum rated tensile strain	0.25%
I_c (self-field, 77K)	140 A

B. Function and relationship of three Models

Three numerical models were established using COMSOL and ANSYS software packages, for achieving and verifying the new AC loss calculation method. Simple descriptions of these three models are as follows:

- *Model A*: This is an “entire motor” model which is established in COMSOL Multiphysics using A-H formulation, which considers the highly non-linear properties of HTS material. This model calculates the magnetic field of motor and AC loss in HTS winding, but the simulations using this model normally take about several days to compute.
- *Model B*: This is an “entire motor” model which is established in ANSYS Maxwell by the already existing motor module in ANSYS, which does not consider the non-linear properties of HTS material but set a very high conductivity of 5.8×10^{17} S/m for HTS tapes. This model could calculate precise magnetic field of motor in couple of hours. However, obviously, it could not be used to calculate AC loss in HTS winding.
- *Model C*: This is a “winding” model built in COMSOL Multiphysics. Combined with Model B with its computed magnetic field distribution, Model C could assist the fast AC loss calculation in the superconducting motor.

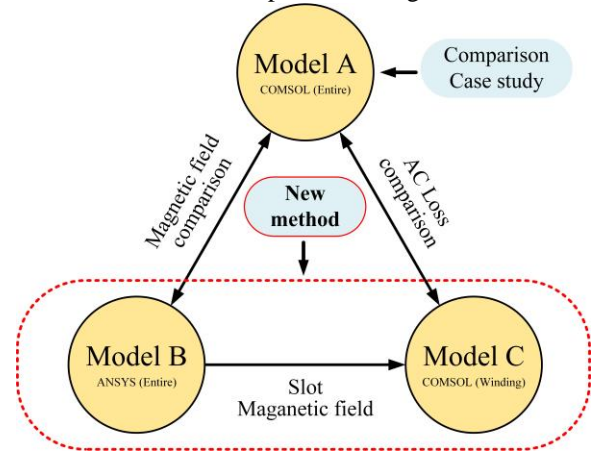


Fig. 2. Function and relationship of three numerical models

Figure 2 illustrates the relationship of three numerical models. To be specific, the new method is implemented by applying the slot magnetic field from Model B into Model C. The Model A was used as the case study. There are two case studies for comparisons with model A: i) comparing magnetic field distribution with Model B; ii) comparing AC loss with Model C. The former one is to observe the impacts of non-linear characteristics on magnetic field distribution in motor, and the latter one is to verify the accuracy of the new method for calculating AC loss. Finally, we also compared the computation time of Model A with the total computation time of Model B and Model C to prove the efficiency of this new method.

The specific features and settings of models are as follows:

- *Model A*
The A-H formulation, a FEM framework proposed in [7], is used for this model. The main principle is to model the HTS armature winding region with Maxwell’s equations (H-formulation) while the rest of the domains are modeled with magnetic

vector potential formulation (A-formulation), especially the boundary between stator and rotor meshes, called rotation line (R-line). The boundary between formulations is called tramodel line (T-line). Fig. 3 shows the location of these two lines in this motor.

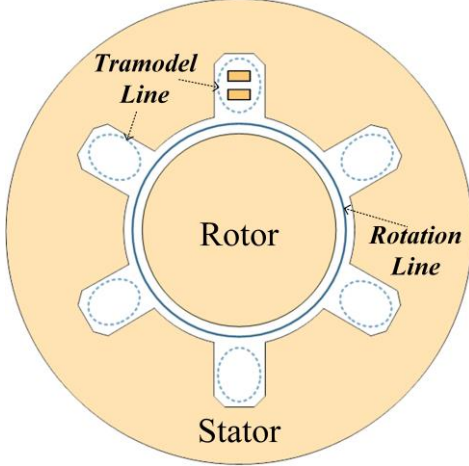


Fig. 3. The locations of T-line and R-line

In this case, the A-formulation is written as follows [19]:

$$\frac{1}{\mu} \nabla^2 A_z + \sigma \frac{\partial A_z}{\partial t} = J_{z\text{ext}} \quad (1)$$

where A_z is the z component of the magnetic vector potential, μ is the material permeability, σ is the material conductivity, and $J_{z\text{ext}}$ is an external current density. The magnetic flux density components in the x and y directions (B_x and B_y) are calculated as follows:

$$B_x = \frac{\partial A_z}{\partial y} \quad (2)$$

$$B_y = -\frac{\partial A_z}{\partial x} \quad (3)$$

The electric field intensity component in the z direction is as follows:

$$E_z = -\frac{\partial A_z}{\partial t} \quad (4)$$

The 2D approximation of the H formulation could be written as two first-order differential equations, as follows:

$$\mu \frac{\partial H_x}{\partial t} + \frac{\partial E_z}{\partial y} = 0 \quad (5)$$

$$\mu \frac{\partial H_y}{\partial t} - \frac{\partial E_z}{\partial x} = 0 \quad (6)$$

The z component of the current density (J_z) is defined as follows:

$$-\frac{\partial H_x}{\partial y} + \frac{\partial H_y}{\partial x} = J_z \quad (7)$$

To model electric characteristic of superconductors with a non-linear resistivity, the power-law and Ohm's law in Eq. (1) [20] are used in this model.

$$\rho = \frac{E_c}{J_c} \left| \frac{J_z}{J_c} \right|^{n-1} \quad (8)$$

where J_c is the critical current density in self field, E_c is critical electric field, criteria to the definition of J_c , and n is the power law index, known as index-value.

- *Model B*

Model B is established in Maxwell 2D module in ANSYS software package. A current source of the same value as Model A is used as the excitation. The HTS winding is set a conductivity close to infinity shown in Table III, without considering non-linear conductivity. Other simulation parameters are presented in the Table III, as well.

TABLE III
SIMULATION PARAMETERS FOR MODEL B

Parameters	Value
HTS conductivity	5.8e17 S/m
HTS relative permeability	0.999991
Boundary type	Vector potential
Mesh type	Length based
Solution type	Magnetic transient
Time step	0.001 s

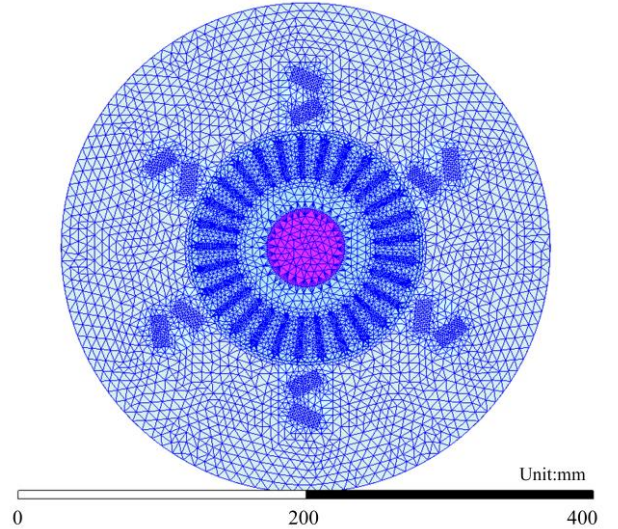


Fig. 4. Generated mesh in Ansys Maxwell

Fig.4 shows the generated mesh of the superconducting motor in ANSYS Maxwell. Every part of the motor was chosen element length based refinement. A very fine grid (2-3 mm maximum element length) is used for armature winding and rotor bar. For stator and rotor iron, the coarse grid with larger grid size (8-10 mm maximum element length) is selected.

- *Model C*

Due to the symmetry of the electromagnetic structure of the motor, the AC loss in slots is completely equal during one cycle. Based on this, a single slot is selected as an AC loss calculation unit, shown in Fig. 5. The schematic diagram of Model C only contains two cross sections from different winding in one slot and an elliptic solution domain. The same current excitation as

in Model A and Model B is applied to this model and the whole model is calculated using H-formulation.

An interpolation function is used to describe the boundary magnetic field in Model C. The two-variable interpolation method proposed here is a very simple and direct method, through a look-up table. At first the magnetic data is obtained from Model B, then those data are formed into interpolation table which will be applied as the boundary magnetic field for Model C. Two variables of the interpolation table are each data point' geometric coordinates (x , y) and time (t), whilst the output variables are magnetic field strength (H_x , H_y). Finally, using a direct interpolation, which is available in COMSOL Multiphysics, implement the definition of the boundary magnetic field.

It is necessary to select limited variable data into the table. In this case, for coordinates date, 20 points were chosen, as a result a 20 segment lines circle was formed as a boundary line surround two windings, shown in the Fig.5. As for time date, we chosen 10 time point in one cycle.

This method significantly simplifies the process and dramatically reduces the computation time required. A similar kind of interpolation has been applied in [21, 22], which directly and accurately expresses the anisotropic behavior in the model and avoids the complex data fitting of $J_c(B, \theta)$.

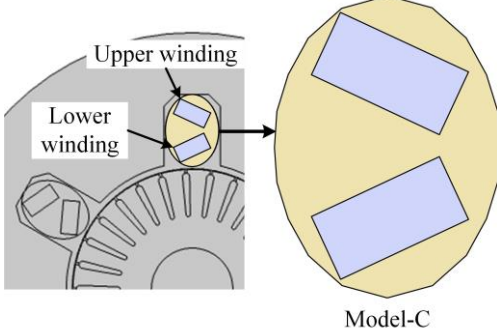


Fig. 5. Schematic diagram of Model C

III. RESULTS AND DISCUSSION

A. Magnetic field comparison in Model A and Model B

Air gap flux is the medium of electromechanical energy conversion in the rotating motor, which converts electrical energy into mechanical energy in asynchronous motors.

The radial flux density waveforms of the Model A and Model B at 100 ms are shown in Fig.6. The two curves have very similar trend. Some parts of two curves are nearly overlapping with each other and in other part, the absolute value of Model A is slightly higher than that of Model B. The error may be caused by the different solution method in different FEM software and mesh setting.

Fig. 7 shows distribution of magnetic flux density and flux lines in Model A and Model B at 100 ms. It is easy to note that magnetic field of the motor is distributed at two poles. Under the same legend range, the two models show little difference in magnetic field distribution, for example, the maximum magnetic flux density happens at rotor for both two models. Thus, it shows that the nonlinear behaviors of superconductors have minor effect on

the magnetic field distribution of HTS motor. Therefore, it is reliable to use Model B as the data source for boundary magnetic field in model C.

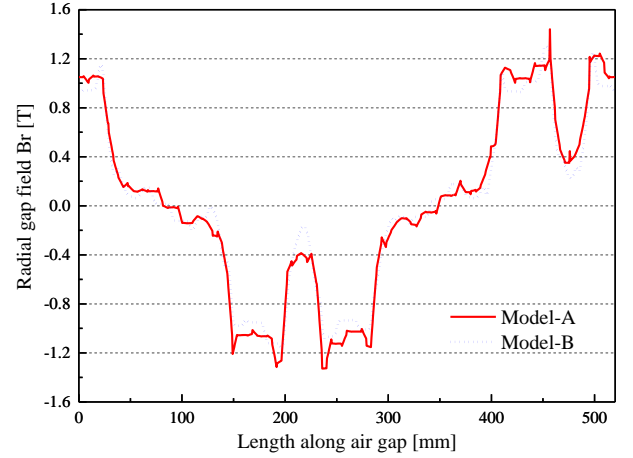


Fig. 6. Radial flux density in the air gap at 100ms

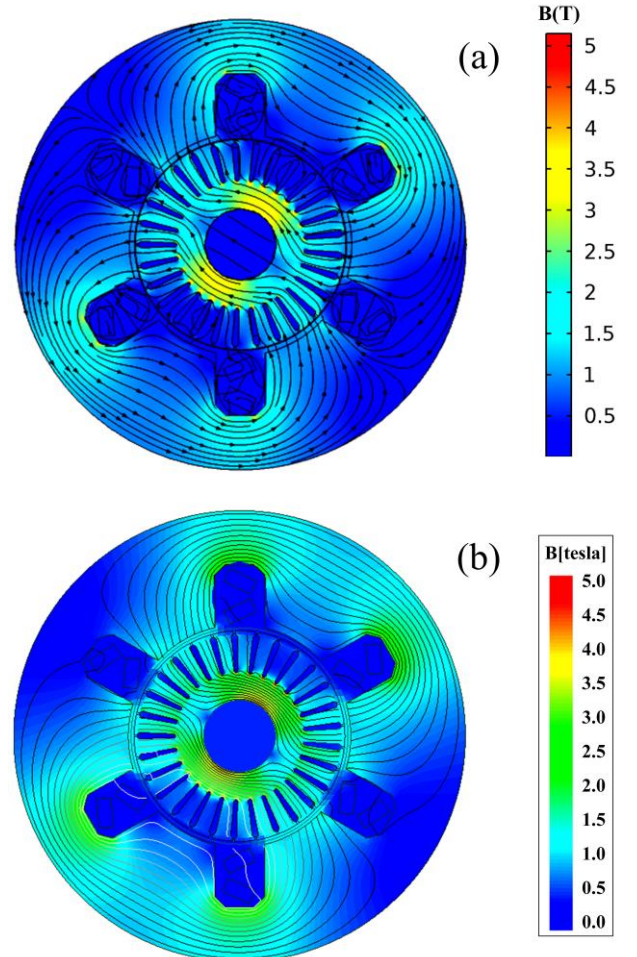


Fig. 7. The distribution of magnetic flux density and flux lines at 100 ms; (a) Model A in COMSOL; (b) Model B in ANSYS.

B. AC loss comparison in Model A and Model C

Fig. 8 compares the distribution of magnetic flux density and current density in Model A and Model C. The difference between two models remains small. For example, from Fig.8(a), the relative error of maximum magnetic flux density between

the two models at 160 ms is 0.3%, and their average magnetic flux density are same at 0.073T. Similarly, the relative error of maximum current density J/J_c is 0.32%, and their average current density are same, at -0.308. These results not only conclude that using interpolation function to define the boundary magnetic could reflect the real magnetic environment around winding, but also means that with real-time background field and coil operating current, the electromagnetic behaviors close to the “entire motor” model can be obtained, however, in much shorter computation time.

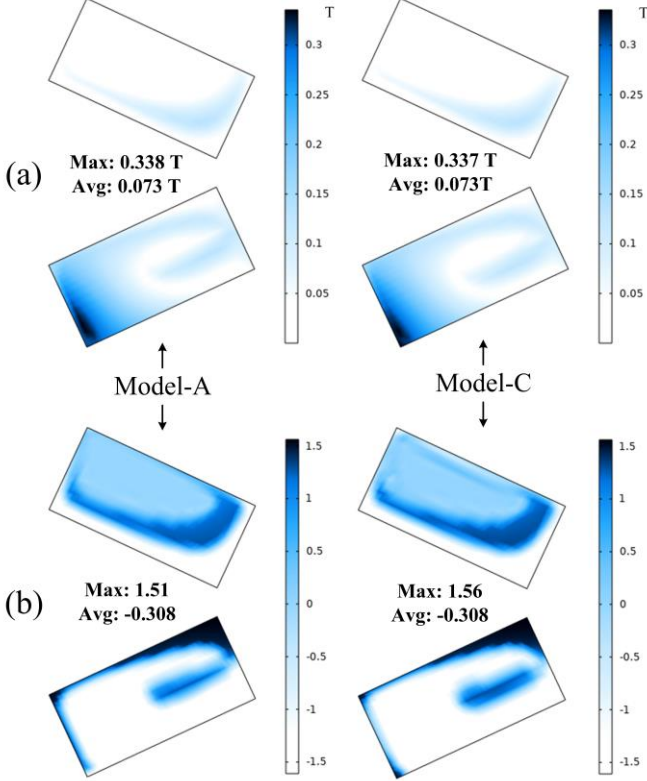


Fig. 8. The distribution of magnetic flux density (a) and current density J/J_c (b) for Model A and Model C at times of 160 ms.

TABLE IV
AC LOSS PER METER PER SECOND

	Model A	Model C	error
Top layer	4.01	3.9	2.5%
Bottom layer	19.52	18.06	7.0%

Fig. 9 (a) shows the instantaneous AC loss of the top layer winding. The two lines overlap exactly, despite some fluctuations at of Model C. Fig. 9 (b) shows the instantaneous AC loss of the bottom layer winding. Curve of Model C fluctuates more dramatically than that of Model A, but two curves show the same change trend. The fluctuations mentioned above might caused by interpolation method which only choose limited data that could not reflect the boundary magnetic smoothly. As for the phenomenon that bottom layer winding AC loss curve shows more fluctuation than top layer winding AC loss curve, this is mainly because the bottom layer winding experience more complex magnetic environment caused by their position close to rotor.

Table IV presents the AC loss, W/m , of the top layer and bottom layer winding. It was noted that AC loss in bottom layer winding is much larger than that in top layer winding. This is simply because bottom layer windings are more closed to the rotor, which is exposed to more complex and stronger electromagnetic field. As for the AC loss errors for two models, error for both the top and bottom layer windings are small, about 2.5% and 7%, respectively.

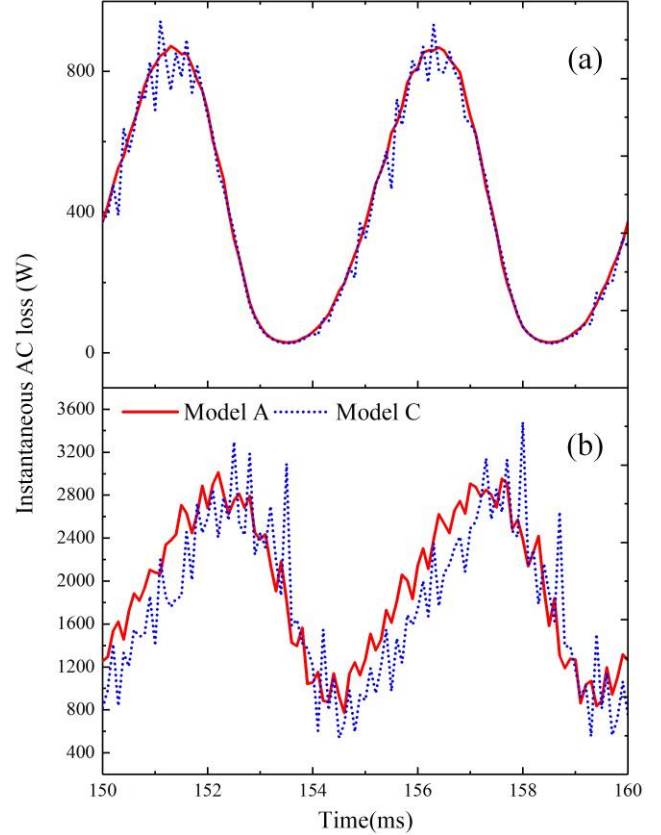


Fig. 9. Comparison of instantaneous AC loss in top layer winding (a) and bottom layer winding (b) for Model A and Model B.

TABLE V
NUMBER OF DEGREES OF FREEDOM OF THREE MODELS
AND THEIR COMPUTING TIME IN 16 CYCLES

Model	A	B	C
DOF	44652	--	4852
Computing time (hours)	48	1.5	0.5

Besides, as tabulated in Table V, the number of degrees of freedom (DOF) of Model A and Model C are 44652 and 4852, respectively, and the computation time of the simulation for 16 cycles take around 48 hours, 1.5 hour and 0.5 hours for Model A, Model B and Model C, respectively, on an i7-4800MQ CPU, 2.70-GHz personal computer. The computation time of ‘boundary field method’ (through Model B and Model C) is much faster than that of Model A.

IV. CONCLUSION

In this paper, three numerical models were established to analyze a 100 kW HTS induction motor. We proposed and validated a new fast-computing numerical method for calculating AC loss in motor.

The overall magnetic field distribution and radial flux density distribution along air gap obtained from Model A and Model B were plotted and compared against each other. The results showed good agreement, which indicates Model B offers fast solution to analyze the magnetic field in HTS motor.

AC loss comparison in top layer winding and bottom layer winding between Model A and Model C showed 2.5% and 7% disagreement, respectively, which is acceptable in AC loss modelling, although there are some fluctuations in instantaneous AC loss of Model C. Furthermore, it was found the average magnetic flux density and J/J_c at a certain time are totally the same. More importantly, the total computation time of new method (Model B plus Model C) for 16 cycles (around 2 hours) is much shorter than that of Model A (around 48 hours).

During the modelling process, to add background magnetic field from Model B into Model C, the interpolation method has been implemented to link these two models. The above results show this way is reliable.

Overall, the 'Boundary field method' proposed in this paper for calculating AC loss is computationally efficient. This numerical modelling idea can be used to analyze 3-D model for getting more precise AC loss or other electromagnetic properties, which is needed to be further applied and investigated in future.

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